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8 Earthworms and Agricultural Management

Earthworms can have a major impact on the rhizosphere by their feeding, casting, and burrowing activities. Although earthworms are relatively large compared with the average diameter of roots of many agricultural crops, they can significantly alter the root rhizosphere as well as bulk soil properties. These impacts have often been overlooked in modern rowcrop agriculture in the United States, but greater interest in reduced tillage systems and concern about agricultural sustainability have prompted researchers and farmers to again consider the potential role of the earthworm. The excellent books by Lee (1985) and Edwards and Lofty (1977) discuss earthworm biology and ecology in great detail, and readers should consult them for more information.

The objectives of this chapter are to summarize the major effects of earthworms on soil properties and plant growth and the effects of agricultural management practices on earthworm populations. We conclude by discussing the potential importance of earthworms in conservation tillage systems, management strategies that may enhance earthworm activity, and areas that need additional applied research.

BASIC ECOLOGY OF EARTHWORMS

Most references to earthworms in the scientific literature deal with the family Lumbricidae, but the ecological

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strategies discussed here apply to other families as well. Although Lumbricidae may have been native to North America as well as Europe, they probably did not survive the Quaternary glaciations. Lumbricidae were reintroduced to much of North America by European settlers during the past 400 years or by migration from unglaciated areas in the south (Lee 1985). This suggests that there may be areas in the glaciated portions of North America that lack particular species of earthworms, because they have not been introduced. Some unglaciated areas of the West Coast may support indigenous non-Lumbricid species (Spiers et al. 1986).

Different species of earthworms occupy different niches and are often grouped by their feeding or burrowing habits. Bouché (1977) proposed the following classification, based on morphological and ecological characteristics, for the European Lumbricids: epigées are litter dwellers and feeders, endogées live and feed in the mineral soil, and anéciques are deep-burrowing worms that live in the mineral soil but typically feed on dead leaves at the soil surface. We will discuss the activities of endogées and anéciques, because only those species will have a major impact on soils in agricultural systems. It should be noted that feeding and burrowing habits of a species also depend on food availability, agricultural management, and edaphic conditions (Lee 1985). The morphological-ecological classifications are, therefore, a general guide to ecological strategies.

While lacking permanent burrows, the endogées generally burrow through the topsoil, ingesting mineral soil and organic materials but preferentially selecting organic materials. Different species ingest organic matter in different stages of decomposition. Lumbricus rubellus, for example, ingests relatively undecomposed organic matter, while Allolobophora caliginosa feeds on well-decomposed material (Piearce 1978). In contrast the anéciques such as L. terrestris (commonly called "nightcrawlers") make permanent, nearly vertical burrows into the subsoil but feed on litter at the surface. They often pull leaves down into their burrows for aging and later feeding. These two major groupings of earthworms can have quite different effects on soils and plant growth and are affected differently by agricultural management.

Earthworms are saprovores, deriving their energy primarily from ingesting dead plant materials. They also obtain nutrition from microorganisms ingested either preferentially or along with organic and mineral matter (Satchell

1983). Although they ingest large quantities of soil and organic matter, they assimilate only a small amount of the carbon ingested, typically one to three percent (Bolton and Phillipson 1976; Uvarov 1982).

THE EFFECTS OF EARTHWORMS ON SOIL PROPERTIES AND PROCESSES

Channels

Earthworms create burrows typically ranging in diameter from 1 to 10 mm. These burrows can conduct water and air rapidly into the soil and provide low-resistance pathways for root growth. The influence of earthworm burrows on water flow is greater on soils that have a low soil matrix permeability. Field and greenhouse experiments have shown large increases in water infiltration rates due to the presence of earthworm burrows (Hopp and Slater 1948; Ehlers 1975; Edwards et al. 1979; Bouma et al. 1982; Kladivko et al. 1986; Zachmann et al. 1987; Kemper et al. 1987). Recent evidence suggests that water will infiltrate in some earthworm burrows even when rainfall amounts are relatively low, especially if rainfall is intense in the initial part of the storm and the soil surface is initially dry (Edwards et al. 1989). Infiltration in macropores produces a different soil water content distribution with depth than in soils without burrows. The role of earthworm burrows and other macropores in movement of water and chemicals through the soil is the subject of much current research.

The rate and location of burrow formation is affected by availability and location of the food supply as well as by soil water content, temperature, bulk density, and penetration resistance (Lavelle 1975; Bolton and Phillipson 1976; Timmenga 1987). Zachmann, Linden, and Clapp (1987) added A. tuberculata or L. rubellus to no-till plots with surface residues and to tilled plots with incorporated residues in Minnesota. Over a six-week period in early summer, both species formed twice as many burrows open to the soil surface on no-till as on tilled plots (Table 8.1). Because the major food supply was at the soil surface in no-till but was buried in the tilled plots, feeding and burrowing activity near the surface was greater with no-till than with tillage. The surface residue also provides a suitable habitat for the earthworms by insulating the soil from

TABLE 8.1. The number of burrows open to the soil surface after six weeks of earthworm activity in Minnesota, as affected by tillage treatment and species.

Tillage treatment	Species	Number of burrows (SE)[a]
Tilled[b]/ incorporated residue	A. tuberculata	14.5 (0.6)
	L. rubellus	15.0 (0.8)
No-till/ surface residue	A. tuberculata	36.5 (3.7)
	L. rubellus	47.5 (4.4)

[a]Measured in 0.06 m^2 subplots inoculated with 13 earthworms each.
[b]Tilled with rototiller to 10-cm depth.
Source: From Zachmann, Linden, and Clapp (1987).

rapid drying or heating in early summer.

Several researchers have counted earthworm burrows or other biopores under different agricultural management systems (Ehlers 1975; Boone et al. 1976; Gantzer and Blake 1978; Barnes and Ellis 1979; Edwards and Norton 1986) and have assessed their continuity from the soil surface to the subsoil with the use of dyes or tracers (Ehlers 1975; Douglas et al. 1980; Germann et al. 1984; Zachmann et al. 1987; Shipitalo and Edwards 1987; Heard et al. 1988). As many as 1,700 biopores (earthworm and old root channels) greater than 1 mm in diameter have been found in one square meter of soil area at a depth of 30 to 38 cm (Gantzer and Blake 1978). Generally, channels are more numerous and continuous in no-till than in tilled fields because the burrow openings in the topsoil are not destroyed each year by tillage. Burrows in the subsoil may persist for many years after their inhabitants have left, even if the burrows are destroyed in the topsoil. Shipitalo and Edwards (1987) found large L. terrestris burrows in the subsoil that had been abandoned for at least twenty-four years. Regardless of whether they extend to the surface, burrows

can aid root development (Wang et al. 1986) and will be discussed in more detail in a later section.

Casts

Organic materials and mineral soil are mixed intimately during passage through the earthworm gut and are excreted as casts. Casts are deposited at the soil surface, in subsurface cavities, or along burrow walls, depending on the species and soil conditions. The amount of casts produced depends on food source and environmental conditions in the soil. Annual surface cast production in agricultural systems ranges from 4 to 90 Mg ha^{-1} in temperate regions (Edwards and Lofty 1977; Lee 1985).

Earthworm casts influence many physical, chemical, and biological conditions of the soil. Casts generally contain more organic matter and available nutrients than the surrounding soil because of the earthworm's selective ingestion of organic materials and the mineralization of those materials during passage through the gut (Lee 1985; Timmenga 1987). Casts often contain higher concentrations of exchangeable calcium, magnesium, and potassium (Lunt and Jacobson 1944) and extractable phosphorus (Sharpley and Syers 1976, 1977) than the surrounding soil. Higher phosphatase (Satchell and Martin 1984) and urease (Syers et al. 1979) activity has also been found in casts. The pH of casts is generally closer to neutral than that of the parent soil (Edwards and Lofty 1977). Microbial populations are larger in casts than in the surrounding soil (Parle 1963) due to proliferation of microbes during passage through the gut and in the cast after deposition. Although total microbial populations are greater, there is evidence that cells of some microorganisms are destroyed during their passage through the earthworm gut (Edwards and Lofty 1977; Rouelle 1983). Earthworms may act as vectors for bacteria and fungi, including plant pathogens, by ingesting cells or spores in one place and depositing them in casts elsewhere (Rouelle 1983; Shaw and Pawluk 1986).

Casts have generally been found to increase the water-stable aggregation of soils (Hopp and Hopkins 1946a; Lal and Akinremi 1983; Kladivko et al. 1986). Under some pasture conditions, however, surface casting by earthworms caused an increase in sediment losses by erosion (Darwin 1881; Sharpley et al. 1979). These greater sediment losses may be due in part to exposing soil material (casts) in an area otherwise covered with growing plants and protected

from erosion. Shipitalo and Protz (1988) found that freshly deposited moist casts are not very stable, but aging and drying processes increase their water stability. Cast stability, as measured by clay dispersibility in the casts, also varied with the earthworm species and the food source.

Earthworm burrows, especially the "permanent" burrows of anéciques, are stabilized by castings deposited along burrow walls and by mucus excreted by earthworms (Piearce 1981). Burrow walls can thus be viewed as stable, well-aerated soil zones containing higher concentrations of organic matter, available nutrients, and microorganisms than the surrounding soil. Bouché (1975) discussed the "drilosphere," a zone 2 mm thick around burrow walls, as a zone of increased microbial activity due to these conditions. The importance of this zone for increased root growth and nutrient uptake, especially in less fertile soils, needs further investigation.

Mixing

Earthworms mix organic debris and applied inorganic materials (fertilizer phosphorus, lime, pesticides) into the soil and may be very important in cycling organic matter and nutrients in forest, pasture, and no-till ecosystems. Much of the research on soil mixing by earthworms has been conducted in pastures, forests, orchards, or drastically disturbed lands under reclamation. The importance of soil mixing by earthworms in nontilled rowcrop agriculture needs further investigation.

Stockdill (1982) has done much work on the effect of earthworms on pasture productivity in New Zealand. Earthworms incorporate thatch materials as well as applied lime, nutrients, and insecticides. Some species, such as A. caliginosa and L. rubellus, tend to mix the lime laterally, while others such as A. longa mix it vertically (Springett 1983). The incorporation and intimate mixing of phosphate rock pellets with soil by earthworms indirectly increases the availability of phosphorus from the rock (Mackay et al. 1982).

Dietz and Bottner (1981) placed litter labelled with ^{14}C on the surface of a grass land soil and used autoradiography to follow the movement of the ^{14}C into the profile. Most of the decomposition products were transported through the profile by water, while a small portion was mixed into the soil by earthworms. The introduction of L. terrestris to coal spoil banks in Ohio (Vimmerstedt and Finney 1973)

and reclaimed peat in Ireland (Curry and Bolger 1984) resulted in greater litter incorporation than in similar disturbed lands without the earthworms.

Earthworms--Allolobophora tuberculata, Dendrobaena octaedra, L. festivus, and L. terrestris--invaded a New Brunswick mixed forest and dramatically changed the soil profile. The transformation from a typical podzol to a profile with an apparent Ah horizon required only four years (Langmaid 1964). Introductions of earthworms A. caliginosa and L. terrestris into newly reclaimed polders in the Netherlands improved soil structure and decreased thatch accumulations (Hoogerkamp et al. 1983). When overuse of copper-containing pesticides killed the earthworms in an orchard soil in the Netherlands, soil structure rapidly deteriorated and a thatch layer developed on top of the mineral soil (van Rhee 1963).

Timmenga (1987) measured residue mixing and cast distribution in a soil column experiment. Silty clay loam soil was packed into columns (10-cm diameter, 35-cm depth) to a bulk density of 1.0 g cm^{-3}. A water table was maintained 36 cm from the surface. Plant parts from red clover (Trifolium pratense) were added as a food source. The root material was placed at the 5-cm depth, while the shoot material (mostly leaves) was placed on the soil surface. Five earthworms (L. rubellus) were added to each soil column except the controls. Columns were capped, and evolved CO_2 was trapped to monitor decomposition. After thirty days, columns were frozen and sectioned. Cast material and plant remains were collected, and observations of burrows were made at depth increments throughout the column.

The earthworms did not have a noticeable effect on the rate of CO_2 evolution, probably because they do not assimilate organic matter in large quantities. In columns without earthworms, losses in dry weight were 56 and 6.9 percent for shoot and root materials, respectively. In the presence of earthworms, shoot material was almost completely removed from the surface of the soil, while most of the root material was not moved. Horizontal burrows were found near where the roots were buried, indicating that earthworms were active at that depth, but only slight amounts of the root material itself were consumed by the worms. This suggests that the root material lacked palatability or perhaps a microbial population. In the 0- to 5-cm layer, the burrow walls (all cast material) were thick and easy to recognize and recover because of their dark olive green color, rounded shape, and high fiber content. Some of the burrows were blocked with casts. Along the sides of the

columns, the worms had created reinforced burrows made of large amounts of casts. In the 5- to 10-cm layer, the burrow walls were not very thick but could easily be removed by peeling the burrow wall material from the surrounding soil. Most burrows below 10 cm occurred along the sides of the column, where the soil was probably looser, better aerated, and more penetrable than soil inside the column. These burrows along the sides of the column had very thin walls with virtually no recoverable casts, and some burrows showed only slightly smeared tracks. Burrows were found in the soil close to the water table, suggesting that a high soil water potential per se does not restrict the burrowing depth of L. rubellus.

Few casts were found in the 20+ cm layer, and cast weight was negatively correlated with depth in the column. The bulk of the cast material was found on the surface (16%), and in the 0-5 (46%), the 5-10 (22%), and the 10-15 (12%) cm layers. The average dry weight of casts recovered from each column was 34.28 g (SE 0.91). The average dry weight of the earthworms, measured in a subsample of the population before the experiment, was 0.094 g $worm^{-1}$ (SE 0.0066). The egestion rate of L. rubellus in the experiment was estimated at 2.43 g dry cast weight g^{-1} dry worm weight day^{-1}, calculated for columns from which five worms were recovered.

THE EFFECTS OF EARTHWORMS ON PLANT GROWTH AND YIELD

Root Growth

Root growth can be increased, especially in subsoils or moderately dense soils, by the presence of earthworms or their burrows (Figure 8.1). Edwards and Lofty (1978, 1980) added earthworms to small field plots and to intact soil columns taken from direct-drilled (no-till) plots and found increased root growth compared to the noninoculated treatments (Table 8.2). The root distributions were closely correlated with the zones of activity of the particular earthworms added. Deep-burrowing (anécique) species (L. terrestris, A. longa) promoted deeper root growth, and the more shallow-dwelling (endogeic) species (A. caliginosa, A. chlorotica) promoted shallow root growth. Tests with artificially formed burrows compared with earthworm burrows suggested that the improved root growth resulted from both

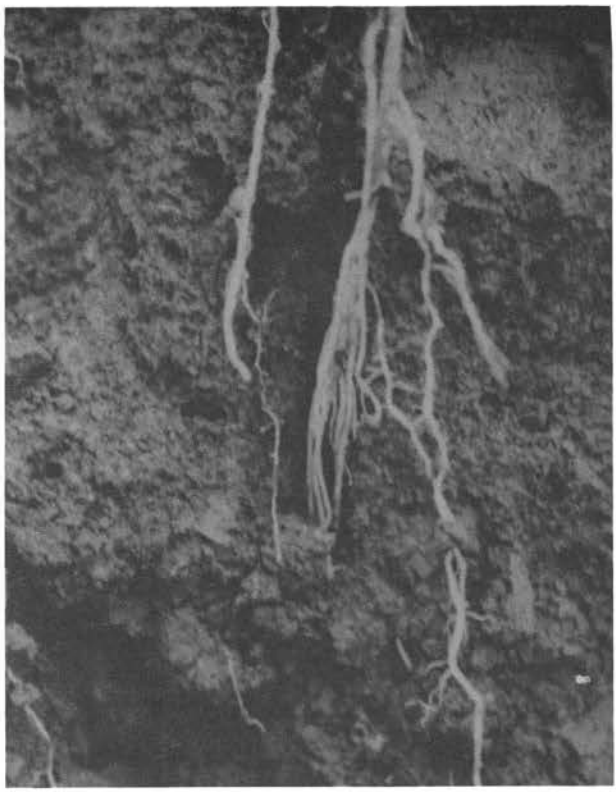

Figure 8.1. Corn roots growing in earthworm burrows at a depth of 60 cm.

the physical ease of root growth in preformed channels and the greater availability of nutrients in the burrow walls. Banded applications of nitrogen and phosphorus to soils usually result in root proliferation in those bands (Duncan and Ohlrogge 1958). Roots would tend to proliferate in earthworm burrows due to available phosphorus from cast material and available nitrogen from urine or mucus excretions.

Root proliferation in earthworm burrows in the subsoil has been observed by several researchers. Ehlers et al. (1983) found that oat roots were detectable within biopores below a 10-cm depth in untilled loess soil and below a 15-cm depth in tilled soil. The percentage of roots found in

TABLE 8.2. Root growth of barley grown in undisturbed profiles of silty clay loam soil, as affected by earthworm additions and tillage treatment.

Tillage treatment	Earthworm species	Root weight[a] (g)
Direct drill	None	0.39
Direct drill	L. terrestris[b]	0.79
Direct drill	A. long[ab]	0.78
Direct drill	A. caliginosa and A. chlorotica[c]	0.62
Plow	None	1.04

[a]Standard error = 0.13g.
[b]Five mature earthworms added per box.
[c]A total of ten mature earthworms added per box.

Source: From Edwards and Lofty (1978).

biopores increased with soil depth, and below 50- cm nearly all the roots were in biopores. On a silt loam soil in Illinois, Wang, Hesketh, and Wooley (1986) found soybean roots entering burrows at depths of 30 to 45 cm. The roots then grew within the burrows down to the point where the burrows ended, which was as deep as 130 cm. If a taproot did not encounter a burrow by the time it reached the 45-cm depth, the root tip died.

In polder soils of the Netherlands, large-scale inoculations of earthworms were made to study the effects of earthworm activity on soil properties and plant growth. Van Rhee (1977) found greater total root growth and a higher ratio of thin to thick roots (less than 0.5 mm compared with 0.5-5 mm) of young apple trees in the earthworm plots, probably due to increased soil aggregation. Only very small differences in fruit yields were observed, however. A deep-burrowing species of earthworm (A. longa) was introduced to some New Zealand pasture soils that were already inhabited by shallow-dwelling earthworms. The inoculated plots had increased soil porosity at the 10- to 20-cm depth and greater root development in the 15- to 20-cm depth than the control plots (Springett 1985). Pasture growth was increased during some seasons.

Shoot Growth and Yield

Although root growth increases under some conditions as a result of earthworm activity, this may or may not result in increased shoot growth or crop yield in any given year. Extensive research on earthworms in pasture soils has consistently shown increased pasture production in the presence of earthworms. Lee (1985) discusses the history of pasture improvement by earthworm introductions in New Zealand, and an example of Stockdill's work is presented in Table 8.3. Earthworms were introduced in 1949 at various points in an established pasture. After four years, the earthworms were well established at the points of introduction and were improving early spring growth of the pasture. Once the earthworms were established, they advanced about 10 m per year across the field. Measurements of pasture production were made in the 1965-66 growing season in three different zones of the field: zone 1, where earthworms had been established for ten years; zone 2, where earthworms were just entering during 1965-66; and zone 3, where there were still no worms. The 30 percent higher yield in zone 1 over zone 3 was attributable to incorporation of thatch material, improvement in porosity and infiltration, and mixing

TABLE 8.3 Pasture yields in New Zealand, as affected by earthworm (A. caliginosa) introduction.

	Dry matter yield		
	Zone 3 (no worms)	Zone 2 (worms entering)	Zone 1 (worms established)
	----------Mg ha^{-1} ----------		
Spring 1965	3.26	3.61	4.10
Summer 65/66	3.76	4.12	4.78
Autumn 1966	2.38	3.45	3.22
Total 65/66	9.40	11.18	12.10

Source: From Stockdill (1982).

of lime and nutrients into the soil (Stockdill 1982). Earthworms have also increased pasture production in polder soils in the Netherlands (Hoogerkamp et al. 1983).

The growth of various crops as affected by earthworms has been measured in many pot experiments. Hopp and Slater (1949) conducted a series of experiments with soybeans, lima beans, millet, wheat, and hay grown in greenhouse pots, soil frames, or large barrels with either no earthworms, dead earthworms, or live earthworms added. All crops had greater yields with dead earthworms compared with no earthworms, due to chemicals released from the decaying earthworms. Additional yield increases occurred in the presence of live earthworms, on those soils that were initially poorly structured or artificially puddled, presumably due to improved soil structure caused by earthworm activity. With large populations of earthworms, van Rhee (1965) found increases in shoot dry matter production of wheat, grass, and clover, but decreases in pea yields. Atlavinyte and Zimkuviene (1985) planted barley in soil pots at three different bulk densities, with or without earthworms and N-P-K fertilizer. Earthworms accelerated germination and heading and increased grain yield in the soils at higher bulk densities (1.3 and 1.5 g cm^{-3}). During a twelve-month study, A. caliginosa enhanced early growth and increased shoot dry matter production of perennial ryegrass on a silt loam soil from which the topsoil (0 to 15 cm) had been stripped (McColl, Hart, and Cook 1982).

Several researchers have suggested that earthworms stimulate plant growth by the production of metabolites similar to plant growth hormones or other biologically active substances. Graff and Makeschin (1980) found greater shoot dry matter production of ryegrass, both in pots in which earthworms were removed after eleven days of activity and in pots watered with eluates from the earthworm pots. They suggested that earthworms released some yield-influencing subtances into the pots. Edwards et al. (1985) reported that earthworm casts enhanced plant growth and germination above that due to the enriched nutrient content alone. Springett and Syers (1979) observed rye-grass roots growing into surface casts of L. rubellus but not A. caliginosa. They suggested that the negatively geotropic growth may be due to some auxin-like substance in the casts and not solely to gradients of available phosphorus. Increased concentrations of vitamin B12 in the soil have been attributed to earthworm activity (Atlavinyte and Daciulyte 1969) or to the stimulation of microbial activity associated with earthworms.

EFFECT OF AGRICULTURAL MANAGEMENT ON EARTHWORMS

Tillage and Cropping

Agricultural management systems affect earthworm populations and activity by affecting the amount, quality, and location of food for the earthworms and by changing the physical and chemical properties of the soil. Earthworm populations are larger under permanent pasture than under continuously cropped land (Evans and Guild 1948; Hopp and Hopkins 1946b; Barley 1959) primarily because of the much greater supply of organic materials under pasture. The loss of a surface insulation layer may also contribute to the decline in earthworm populations with cultivation, especially in harsh climates (very cold or very dry). The tillage operation itself will kill some earthworms, but this generally represents only a minor contribution to the population declines on tilled land.

After a pasture is plowed and cultivated, earthworm populations remain stable for some time because a large food supply is still available. With continued cultivation, the populations decline (Evans and Guild 1948) and the species distribution changes. Farmers are interested in knowing how quickly earthworm populations will change in response to changes in management practices. Because populations will change as land goes into government "set-aside" programs or into crop rotations with hay crops, for example, some practical management options for increasing populations may be available to farmers. It appears hat several years of pasture is sufficient to rebuild large earthworm populations, but that plowing and cultivation will reduce those populations again within several years. Barley (1959) compared earthworm populations in a two-year rotation (wheat-fallow), a four-year rotation (pasture-pasture-fallow-wheat), and permanent pasture in Australia. The two-year rotation had very few earthworms at any sampling time. In the four-year rotation, earthworm biomass was nearly as great after the two years of pasture as in permanent pasture, but dropped to about one-fourth the biomass after the fallow and wheat years. Possibly the use of no-till rather than plowing after the pasture years would slow the rate of decline of earthworm populations.

The influence of different tillage practices on earthworm populations and activity has been studied primarily in Europe, where climatic conditions are very different than in many parts of the continental United States. Direct

drilling of wheat or barley crops generally resulted in greater earthworm populations than did plowing (Barnes and Ellis 1979; Gerard and Hay 1979; Edwards and Lofty 1982; Clutterbuck and Hodgson 1984). Deep-burrowing (anécique) species were affected more by tillage than the shallow dwellers. The plow destroys the natural feeding habitat of the anécique by burying the residues below the soil surface. Tillage destroys the upper portion of the permanent burrows of anéciques, which must then be reconstructed. Replacement of individuals killed during the tillage operation itself is slower for anéciques than for shallow dwellers because of lower reproductive rates. But even the shallow dwelling earthworms had larger populations with direct drilling than with plowing, probably because of less destruction by cultivation operations, organic materials being available over a longer period of time, and insulation of the soil surface. A surface mulch or protective layer was important in maintaining earthworm populations through the winter in north-central and mid-Atlantic regions of the United States where soils freeze (Hopp 1947; Slater and Hopp 1947).

In Indiana, Mackay and Kladivko (1985) found twice as many earthworms under no-till as under moldboard plowed plots growing continuous soybeans, but found no differences between the tillage systems in continuous corn (Table 8.4). Populations were very low in the continuous corn plots sampled. Mackay and Kladivko suggested that the wider C:N ratio of corn residue compared with soybean residue and the application of anhydrous NH3 and the soil insecticide terbufos in the corn plots may have limited the populations. De St. Remy and Daynard (1982) also found no consistent increases in the numbers or biomass of earthworms under no-till corn in Ontario, Canada. However, Lal (1976) found an average five-fold increase in the numbers of earthworm casts under no-till compared with disc plowing under both continuous soybeans and corn in Nigeria. In Georgia, House and Parmelee (1985) found higher earthworm populations with no-till than with moldboard plowing in a sorghum-soybean rotation that included winter cover crops.

Organic matter additions, in the form of manures or sewage sludges, greatly increase earthworm populations (Edwards and Lofty 1982; Standen 1984; Mackay and Kladivko 1985). Some sludges may have a brief initial detrimental effect (Edwards and Lofty 1982), presumably because of high ammonium concentration. In general, the greater the amount of organic matter added to soils, the higher the earthworm populations will be. Nitrogen content and other quality

TABLE 8.4. Earthworm populations as affected by crop and tillage practice, autumn 1983, in Indiana.

Crop	Tillage	Earthworms no. m^{-2} (SD)	
Corn	Plow	8	(8)
Corn	No-till	16	(8)
Soybeans	Plow	62	(23)
Soybeans	No-till	141	(9)
Clover/ryegrass	Pasture	470	(5)
Clover/ryegrass	Pasture[a]	1,298	(75)

[a]This site also received large applications (more than 10 Mg ha^{-1} y^{-1}) of dairy cow manure from the barnyard.

Source: From Mackay and Kladivko (1985).

components of the organic material also affect earthworm growth. For example, Shipitalo, Protz, and Tomlin (1988) offered excess food to L. terrestris and L. rubellus in soil pots in the lab. They estimated food ingestion as the rate of disappearance of food from the soil surface. They found that both species ingested the most food and gained the most weight when offered alfalfa or red clover leaves and had intermediate ingestion and weight gain with corn leaves, but rejected bromegrass leaves as food and therefore lost weight.

Fertilizers and Pesticides

There are conflicting reports on the effects of inorganic fertilizers on earthworm populations in the field. Fertilizer additions increase plant growth and therefore increase the rate of food supply--dead roots and residues--available to earthworms. The acidifying effect of some inorganic fertilizers may account for population reductions that have been observed (Lee 1985). Earthworm species differ in their optimal pH range (Edwards and Lofty 1977), but many species tolerate a soil pH between 5 and 7.

Earthworm populations have been shown to increase with increasing nitrogen rates up to 192 kg N ha^{-1} applied as $Ca(NO_3)_2$ (Edwards and Lofty 1982). When farmyard manure

plus $(NH_4)_2SO_4$ or $NaNO_3$ was added to cropland, Edwards and Lofty (1982) found larger earthworm populations with $(NH_4)_2SO_4$, which conflicted with earlier research. Potter, Bridges, and Gordon (1985) found earthworm populations decreased with increased NH_4NO_3 rates and were correlated with decreased soil and thatch pH over the 6.0-4.5 pH range on turfgrass. Gerard and Hay (1979) found earthworm populations increased with nitrogen additions up to 50 or 100 kg N ha^{-1} as $Ca(NO_3)_2$, and stayed the same or decreased slightly at 150 kg N ha^{-1}.

There are no published reports of field experiments to assess earthworm response to the more common nitrogenous fertilizer forms used for corn production in the United States--anhydrous ammonia, urea, and urea-ammonium nitrate (UAN) solution. Fertilizer placement--whether surface broadcast or banded or injected--and timing may also affect earthworm response. Ammonia itself is toxic to earthworms, but the overall effect on field populations of injecting anhydrous ammonia is not known. Because the location of earthworms in the profile and their age distribution change throughout the season, mortality might be lessened by prudent timing of chemical application (preplant vs. side-dressed ammonia in corn, for example).

Data on the effect of different pesticides on earthworm populations or activity were compiled by Edwards (1980) and by Lee (1985). Many insecticides and fungicides are toxic to earthworms, but many herbicides are relatively harmless. Again, the placement of the pesticide (broadcast vs. banded over the seed row) may affect earthworm mortality by affecting the proportion of the population exposed to the chemical.

SUMMARY AND IMPLICATIONS

Earthworms are an important component in the soil ecological system. Earthworms form burrows that can improve water infiltration, drainage, and aeration of the soil profile, as well as increasing the extent and intensity of rooting. Following aging or drying, cast material is very stable and generally improves soil tilth, although fresh, moist casts are usually very unstable. Cast material and mucus secretions tend to stabilize earthworm burrows while providing a nutrient-rich lining of the burrow that may further increase root proliferation. Earthworms mix organic materials and surface-applied fertilizers and lime into the soil, both actively by burrowing

and feeding and passively as a result of water transport of materials into their burrows. Thatch and root mat layers have been incorporated into the soil, enhancing root development and water infiltration. Incorporation of surface residues by earthworms also speeds their subsequent degradation by other soil organisms.

The improvements in soil properties brought about by earthworm activity would be expected to increase root growth or plant yield primarily under some type of "stress" condition. Physical stresses--compaction, dense subsoils, crusting, low water infiltration or water availability, poor aeration--and chemical stresses such as low fertility are quite common and offer opportunities to explore the potential importance of earthworms in modern rowcrop agriculture. The use of earthworms to help reclaim coal spoils (Vimmerstedt and Finney 1973) and peat bogs (Curry and Bolger 1984) are examples of the importance of earthworm activity in amelioration of stressful plant habitats.

Earthworms may be more important in no-till and other reduced tillage systems than in conventional moldboard plowed systems, not only because populations are higher under no-till but also because mechanical mixing and loosening by tillage is diminished. When residues are not incorporated by a plow, they can be slowly incorporated by earthworms and other organisms. In the absence of mechanical loosening of the soil, earthworm burrows and casts may become more important for good root development. Increased earthworm activity may partially substitute for the beneficial effects of the moldboard plow. The topsoil will not be as "well mixed" by earthworms as by a plow, and different management strategies may be needed to fully utilize the potential of the biological populations.

Several agricultural management strategies can be used to increase earthworm populations and activity. The particular strategy employed will depend somewhat on whether anécique or endogeic earthworms are of greater interest in that system. Increasing the amount and quality of the food source available, including plant residues and manures, is probably one of the most important ways to increase populations in agricultural fields. Leaving the soil surface covered with organic materials, both as a feeding habitat for deep-burrowing species and as a protective mulch against rapid freezing or drying, will also promote earthworm populations and may prolong their active period in the spring and autumn. Growing winter cover crops on either tilled or nontilled fields may increase populations by adding more food and protecting the surface. Elimination of

tillage will be especially beneficial to deep-burrowing species because their permanent burrows will not continually be destroyed. Modifications in the use of pesticides and inorganic nitrogenous fertilizers may reduce earthworm mortality, and drainage of wet soils may promote larger earthworm populations.

Additional research is needed in many areas of earthworm agroecology. Some of the questions that are important include: How significant is the "drilosphere" for root proliferation and plant nutrient uptake under different soil conditions? Can the excretion of organic metabolites or growth hormones by earthworms be important in plant growth? How much can the use of winter cover crops increase earthworm populations within a typical crop rotation? How significant would mixing activities be in no-till or other reduced tillage systems? Under what soil conditions would improvements in soil physical properties by earthworms be both large and important? Can changes in form, timing, or placement of fertilizers and pesticides reduce any adverse effects on earthworms while still fulfilling their function? Answers to these questions will help improve agricultural management systems.

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